

International Journal of Modern Physics D
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The Tianlai project: a 21cm cosmology experiment

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Received Day Month Year

Revised Day Month Year

Communicated by Managing Editor

In my talk at the 2nd Galileo-Xu Meeting, I presented several different topics in 21cm cosmology for which I have done research. These includes the 21cm signature of the first stars^{1,2}, the 21cm signal from the IGM and minihalos³, effect of dark matter annihilations on 21cm signal⁴, the 21cm forest by ionized/neutral region⁵, and the 21cm forest by minihalo and earliest galaxies^{6,7}. In this conference proceeding I shall not repeat these discussions, but instead focus on the last part of my talk, i.e. the *Tianlai* project, an experiment effort on low redshift 21cm intensity mapping observation for dark energy measurements.

Keywords: 21cm; dark energy, baryon acoustic oscillation

1. Introduction

The ground state of the neutral hydrogen atom are hyperfine splitted by the interaction between the magnetic dipole of the electron and proton. Photons with 21cm wavelength (1420 MHz in frequency) are emitted or absorbed by the transition between these hyperfine structure states. As the neutral hydrogen constitutes about 3/4 of the baryon matter in the Universe, these 21cm photons provide a very useful tool for us to gather the information about the universe. Observations of the 21cm emission have long been used to map out the gas distribution in the Milky Way and the nearby galaxies. A very important evidence for the existence of dark matter comes from the observation of rotation curves, and the 21cm observation is one of the primary means of measuring the rotation curve.

During the last decade, there is an explosion of interest on 21cm observation. This has been driven by developments in both science and technology. With large amount of data coming from high precision cosmic microwave background (CMB) experiments, large scale galaxy redshift surveys, type Ia supernovae, etc., an inflationary cold dark matter model with cosmological constant (Λ CDM) has emerged as the concordance model of cosmology, which provides reasonably good and consistent description of most cosmological observations at a quantitative level⁸. It then becomes interesting and plausible to investigate how the first stars and galax-

ies form in such a universe. With the discovery of the Gunn-Peterson trough in the redshift ($z > 6$) quasars⁹, the epoch of reionization (EoR) begin to attract strong interest from observers and theorists alike. As most of the gas in the Universe is neutral before reionization, it is natural to consider the redshifted 21cm line as an important observational probe of the EoR. At the same time, from a technological perspective, the developments in digital electronics leads to the concept of “software telescope” which allows substantially larger and more precise interferometers to be built, and the digital signal processing means that one can remove foregrounds and extract the 21cm signal even when the foregrounds are orders of magnitude greater than the signal. Currently, several dedicated 21cm experiments, including the LOFAR in Europe(<http://www.lofar.org>), MWA in Australia (<http://www.haystack.mit.edu/ast/arrays/mwa>) and the 21CMA in China (<http://21cma.bao.ac.cn>) have started to take advantage of these developments and look for signs of reionization.

The 21cm experiments draw much lesson from the CMB experiments. Unlike previous radio astronomy observations where one tries to obtain high signal-to-noise maps of individual radio sources, in the CMB experiments low signal-to-noise ratios per pixel are standard fare, and instead of maps of single sources, statistical variables such as the angular power spectrum plays the central role. This new approach greatly reduced the technical and financial demand on the experiment. Thus, all of the EoR 21cm experiments are designed to measure *statistics* of 21cm signal. It is then realized that the same principle, now dubbed as *intensity mapping*, can also be applied to experiments at lower redshifts^{10,11}. A specific application would be observation of the *baryon acoustic oscillation* (BAO) features on the matter power spectrum¹².

2. Baryon Acoustic Oscillation

The BAO are just sound waves in the baryon-photon fluid before the decoupling of photons from baryons at the epoch of Recombination. Due to the characteristic scale of cosmic expansion, it left wiggles on the matter power spectrum. On large scales, the galaxies number density distribution trace the dark matter density distribution, so the same feature also appears on the galaxy power spectrum. Such features, with the first peak at the $\sim 100h^{-1}\text{Mpc}$ scale, have been detected in galaxy redshift surveys such as the SDSS¹³ and 2dF¹⁴. Given a cosmological model, the absolute scale of the BAO features can be calculated, thus it may serve as a standard ruler in cosmology, and using it one can measure the angular diameter distance $D_A(z)$ and the Hubble expansion rate $H(z)$, as a distance in the direction perpendicular/parallel to the line of sight is given by

$$\begin{aligned} r_{\perp} &= (1+z)D_A(z)\Delta\theta, \\ r_{\parallel} &= \frac{c\Delta z}{H(z)}. \end{aligned} \tag{1}$$

Observation of the scales at different redshifts can then be used to determine the cosmological model parameters. In a model with dark energy equation of state $w(z)$, these are given by

$$\frac{H(z)}{H_0} = \left[\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_X e^{3 \int_0^z \frac{1+w(z)}{1+z} dz} \right]^{1/2} \quad (2)$$

and

$$D_A(z) = \frac{c}{1+z} \int_0^z \frac{dz}{H(z)}. \quad (3)$$

From such observations, the properties of dark energy can be measured. Indeed, in the Dark Energy Task Force (DETF) report¹⁵, the BAO method was recognized as one of the primary probes of dark energy. The underlying physics of the BAO is relatively clear, so it allows better modeling and control of the systematic errors. At the same time, high statistical precision can be achieved with surveys of large effective volumes. A number of experiments, such as the SDSS-III BOSS, the WiggleZ, the BigBOSS, and the LAMOST¹⁶, have been or are being planned to exploit this. Even more ambitious projects, such as the Sumira (WFMO) on the Subaru telescope, and the JDEM-ADEPT space telescope have also been considered.

The same measurement can be made with the 21cm intensity mapping experiment. The 21cm emission from a large scale “cell” would be proportional to the matter density in that cell, so the fluctuation of the 21cm could also reveal the BAO feature. Recently, this has been demonstrated in principle by correlating the GBT observed 21cm emission in a small patch of sky at $z = 0.8$ with the optically detected galaxies in the Deep2 survey same region¹⁷.

3. Design of the experiment

The BAO features are only “wiggles”, its detection requires high precision measurement of the matter power spectrum. To beat down the cosmic variance in such measurement, very large volume is required. Essentially, one needs to observe a sizable fraction of the cosmic lightcone for which we can observe, hence large sky area is required. It is also necessary to make the observation at different redshifts. To probe the dark energy, the relatively low redshift range $0 < z < 2.5$ are perhaps most useful, because the dark energy becomes dominate at relatively low redshifts.

The primary difficulty in 21cm observation is foreground. The largest foreground in the relevant frequency range is galactic synchrotron emission, which scales as $\nu^{-\alpha}$, where $\alpha \sim 2.5$. Other foregrounds include bremsstrahlung, point radio sources, etc. Fortunately, most foregrounds, though much stronger than the 21cm signal, are very smooth in frequency, whereas the redshifted 21cm signal varies in the frequency. Thus, if one looks in one direction, one can remove the smoothly varying part of the frequency spectrum, and recover the rapidly varying 21cm signal.

However, thermal noise could also produce apparant variations in frequency. It is therefore necessary to achieve very low noise temperature. The noise temperature

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per pixel is given by

$$\delta T = \frac{T_{sys}}{\sqrt{2\Delta\nu t}} \quad (4)$$

where $\Delta\nu$ is the bandwidth, t the integration time on that pixel, and T_{sys} is the system temperature, which is generally given by incoherent sum of the sky temperature and the noise temperature in the receiving system, $T_{sys} = T_{sky} + T_{rec}$. At the frequency of interest (0.4-1.4 GHz), the cool part of the sky (i.e. outside the galactic plane and strong radio point sources) the sky temperature is at the level of a few to a few tens K. If a well designed receiving system is used, we can expect to achieve a total system temperature of 50 – 100K. By contrast, the 21cm signal expected is a few mK. Thus, to achieve $SNR \sim 1$ (i.e. $\delta T \sim \text{mK}$) for a single pixel, $\delta\nu t \sim 10^{10}$. If we require $\Delta\nu \sim 0.1 \text{ MHz}$, the integration time is about 10^5 s per pixel, which is about one day integration time per pixel. Only small patches of sky could be observed with existing radio telescopes at this level.

If one wants to build a dedicated telescope for the 21cm intensity mapping observation, how should one proceed? Interferometer array would be a better option than single dish, since the interferometer is more stable against variations in system gain, which is very important in the survey of large scale structure.

As one can see from the above equation, the brightness sensitivity can not be improved with an increased in telescope aperture. Instead, one needs multiple receivers, either on a single telescope, or on multiple telescopes, to increase the total integration time. Note that one may still detect the BAO signal from a large number of pixels even if the individual pixel has SNR less than 1. To increase the number of pixels, one has to increase the observed area of sky. However, if the observed area of the sky is increased at the expense of decreasing the integration time on individual pixels, the overall sensitivity can not be greatly improved. The instantaneous field of view should also be large.

To resolve the BAO peaks, compact interferometer arrays with longest base line of about a hundred meter seems to be a good compromise. At $z \sim 1$, this would give a best resolution of about 14 arcmin, corresponding to a comoving scale of about $10h^{-1}\text{Mpc}$. Most baselines would be about half of this size, corresponding to scales twice large. This would provide sufficient angular resolution to observe the higher BAO peaks in the matter power spectrum.

In Ref. 10, radio telescope with cylinder design was proposed as a possible way to build such an interferometer with low cost and fast survey speed. The low frequency cylinder reflectors can be built with low cost, and it provides a way to realize large field of view observation.

In Fig. 1, a tentative design of the array is shown. Five cylinder reflectors are arranged to lay side by side. The axes of the cylinders are north-south oriented, with 15m-20m width and 100m length. Receiver feeds are packed along the focus line of the parabolic cylinders, with a spacing of half wavelength to avoid multiple peaks in the synthesis beam profile. If we are to observe redshift 1, the half wavelength is

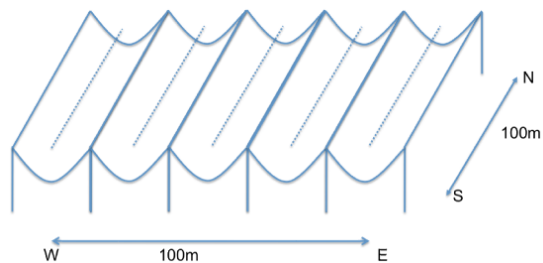


Fig. 1. The basic cylinder array design layout.

about 21cm, so there would be about 500 dual polarization feeds along each cylinder^a. The whole array would produce about 5000 signal inputs. For the convenience of Fast Fourier Transform (FFT), we will choose to have $2^9 = 512$ feeds per cylinder.

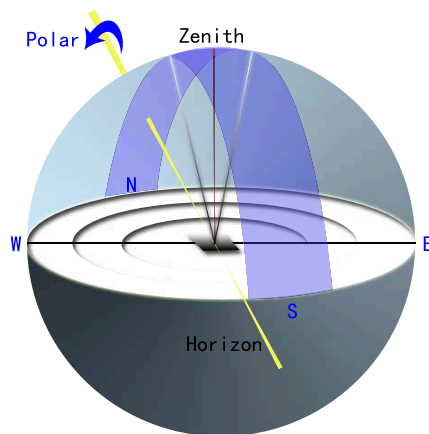


Fig. 2. The instantaneous field of view of the telescope. As the Earth rotates, the field of view scans across much of the sky.

The instantaneous field of view is a narrow strip along the north-south direction passing the zenith. In principle the strip may extend to horizon, if large FOV feed is used in the cylinder. In practice, the strip would not extend that far.

The cylinders shown in Fig. 1 is of the on-axis design, it has the advantage

^aThe dual polarization is essential, because the magnetic field in space cause frequency-dependent Faraday rotations of the polarized foreground radiation, this may induce a modulation in frequency if one observes only one polarization, mimicing the 21cm signal we search for. It is also necessary to calibrate the polarization response with high precision to remove this.

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of providing a symmetric primary beam. Alternatively, off-axis design can be used (see. e.g. Fig.1 in Ref.18). The off-axis design has an unsymmetric primary beam in the east-west direction, but allows easier access to the feeds.

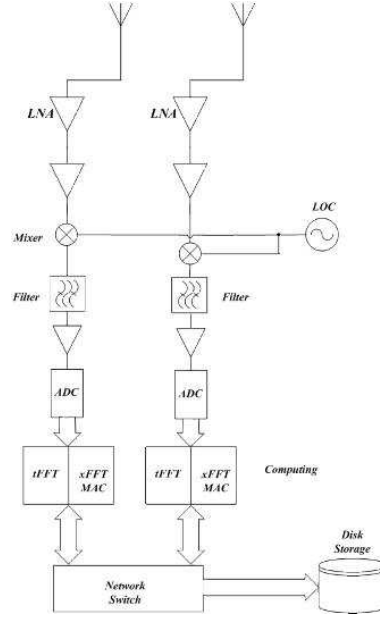


Fig. 3. Receiver Chain.

A schematic of the receiver chain is shown in Fig. 3. The incoming radio wave is reflected by the cylinder reflector, picked up by the feed, then amplified by the low noise amplifier (LNA). The local oscillator (LO) converts the radio frequency (RF) band to intermediate frequency band (IF). The analog to digital converter (ADC) converts the band-filtered analog signal to digital signal. In standard FX correlator, one first makes an FFT of the time series data (tFFT), which reduces the computation from $O(N^2)$ to $O(N \log N)$, then compute the cross correlations between the signals from different receivers but of the same frequency. In the present case, the number of receivers are very large. To further reduce the amount of computation, one can also make a further FFT on the spatial domain (xFFT). The data is exchanged through a network switch, redistributed so that at each computing unit, all the data needed for that FFT is available. For cylinder telescopes, the number of receivers is large along the cylinder, but the number of cylinders is small, so spatial FFT along one dimension is sufficient. The cross correlation between data on the same time and spatial frequency, across the different cylinders are computed (multiply and accumulate, MAC). The results after integration of a time interval of the order of seconds (visibilities) are stored in harddrive for further analysis.

4. Experiment Effort in China

The National Astronomical Observatory of China (NAOC) has started research on the 21cm experiment for dark energy detection. We have named it the *Tianlai* (cosmic sound) project ^b. We are collaborating with Jeff Peterson (CMU), Ue-Li Pen (CITA), Reza Ansari (U. Paris-Sud) and Kris Sigurdson (UBC) in this research.

If we look at the history, we see that in building each telescope based on new technology, one would encounter unexpected problems. Only after these problems are overcome could the new instrument work. As a first step to the full scale experiment, we can build a small scale prototype experiments in which the basic principle and different designs of the experiment can be tested, and possible problems identified. Two small cylinders have been built at the Carnegie-Mellon University by Jeff Peterson and his collaborators. However, the site is not ideal as it is located in central Pittsburgh with a lot of RFI. The NAOC has decided to build three prototype cylinders at a quiet site to further the testing.

The primary criterion for selecting the site is its electromagnetic environment. Site with low radio frequency interference (RFI) is desired. The main source of RFI at this frequency range is mobile phone signal and TV broadcasting. The RFI can not be completely avoided, with high sensitivity they would always appear in the EM spectrum. However, the RFI are typically of narrow bandwidth, and as long as the EM field strength is not too strong as to saturate or distort the output of the amplifier, it is possible to remove them with post processing. Of course, it is best to also have good logistic support, including road, electricity, and communication networking. The presence of existing astronomy or other science research station could save our effort on logistic work.

A possible site of the experiment is in MingTuAn, ZhengXiangBaiQi in inner Mongolia, which is about 400km from Beijing. This is the site of the NAOC solar heliograph. We are also investigate other possible sites. We will make a selection after we have surveyed the RFI of these sites.

In the prototype experiment, we shall combine several inputs into one after the LNA. This would restrict the field of view, but would greatly reduce the required digital electronics and the associated cost, while still allowing a good test of the basic principles.

5. Conclusion

The 21cm experiment is very promising in cosmology, but it is also exceedingly hard. To detect the weak signal out of the huge foreground, it requires unprecedented precision in calibration, not to mention the challenges in building a system with thousands of low noise receivers, and process the data at real time. At present, no 21cm experiment has not yet made a positive detection. It is still an uncharted, inviting

^bThe word tianlai, literally meaning the sky sound, comes from the work of ancient taoist philosopher Chuang-Tzu.

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virgin land. However, we believe that with current technology, the experiment is possible, it just needs to be done.

Acknowledgments

This work is supported by the NAOC, by the center of high energy physics of Peking University, by the John Templeton Foundation “Beyond Horizon” program in China, and by the NSFC grant No.11073024.

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